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An Evaluation of Free-Air Carbon Dioxide Enrichment (FACE) as a Field Method for Investigation of Direct Effects of Carbon Dioxide on Plants

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An Evaluation of Free-Air Carbon Dioxide Enrichment (FACE) as a Field Method for Investigation of Direct Effects of Carbon Dioxide on Plants

ABSTRACT

Free-air carbon dioxide enhancement (FACE) is evaluated as a potential field technique in experiments to investigate direct effects of increased CO_2 on perennial vegetation. The pros and cons of the FACE technique are presented and compared with the closest alternatives.

FACE interferes least with natural wind flow and turbulence, but requires more space and demands extensive sampling. A continuously operated FACE system will require a monitoring and feedback-control system to deal with fluctuating wind velocities and spatial heterogeneities of CO_2. Temporal variability of CO_2 concentration is typically large: 10% of the time (on time scales of minutes to hours), concentration is three to five times the median design value. This characteristic will render mechanistic studies impossible, but studies of ecosystem properties that integrate over long times might be satisfactory. Scale-up from crops to forests is problematic because plot size and CO_2 consumption depend on the square of vegetation height. The CO_2 cost for FACE in a maize crop would be perhaps four times that of an open-top-chamber system; the CO_2 consumption in a forest would be enormous and the logistics practically impossible to attain.

We recommend that use of the circular-type FACE method be limited to studies of ecological questions (i.e., nutrient cycling and competition) and to environments where the vegetation is less than 3 m tall: crops, grassland, or short-stature natural ecosystems. Even in these situations, FACE should be combined with open-top-chamber studies where possible.

An Evaluation of Free-Air Carbon Dioxide Enrichment (FACE) as a Field Method for Investigation of Direct Effects of Carbon Dioxide on Plants

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INTRODUCTION

The need to create a field environment for the study of carbon dioxide effects on vegetation has led to the concept of artificially elevating CO_2 by release through a network of pipes. The history of this free-air CO_2 enrichment (FACE) approach can be traced to studies by a community of agronomists who once pursued methods of fertilizing crops with CO_2: Kretchman (1969), Baker et al. (1970), Allen (1973), and Harper et al. (1973a, b). The idea of extending the FACE method to investigate the global increase of CO_2 and its direct effects on vegetation emerged from Baker and Lambert (1980) and from a workshop that led to a proposal for a FACE program by Enoch et al. (1982). Actual field experience with CO_2 was described in the doctoral theses of Harper (1971) and Allen (1973), and technical aspects were extensively reviewed by Allen (1979).

The FACE technical approach, however, has much in common with another school of thought developed independently by a community of air pollution ecologists. DeCormis et al. (1975) described a grid-release system to study air pollutant effects in vineyards for the French Ministry of Agriculture. The U.S. Environmental Protection Agency's (EPA) Zonal Air Pollution System (ZAPS) released air pollutants through a pipeline network in a prairie grassland (Lee and Lewis, 1975; Lee, Preston, and Lewis, 1978). The U.S. Department of Energy's (DOE) Argonne National Laboratory (ANL) developed its own ZAPS capability (Miller _et al._, 1980), as did the University of British Columbia, Canada (Runeckles _et al._, 1981), the University of Nottingham School of Agriculture, United Kingdom (Greenwood _et al._, 1982), and UK Central Electricity Research Laboratories (CERL) (McLeod, Alexander, and Hatcher, 1983). Shinn _et al._ (1977) designed a related open-air fumigation system to provide linear gradients of exposure; this system was subsequently modified by Laurence _et al._ (1982) and by Reich _et al._ (1982). McLeod and Fackrell (1983) reviewed these relevant air-pollution-effects methods. Although their goals were different than those of FACE, the air-pollution ecologists have contributed much in the way of experience with dynamic dilution, air monitoring, and interpretation of plant response.

The FACE methodology has been viewed by some as a "real world" approach that should be pursued to study the impending CO_2 effects on natural ecosystems. In an objective view it should be considered in the light of necessary tradeoffs, as would all other alternative methods. In this report, we present the pros and cons of FACE methodology, suggest the manner of optimum data interpretation, and make recommendations for FACE employment.

THE PROS AND CONS OF FACE METHODOLOGY

The definition of the FACE approach is to apply a network of pipes or plenums near the ground in a design that will elevate CO_2 to the ambient air without placing an enclosure or "chamber" around the plants.

CHAMBER EFFECTS

Allen (1982) reviewed the research experience of several investigations with either outdoor controlled-environment chambers, open-top chambers, open-air enrichment (FACE), or greenhouses. He concluded that the closest alternatives to FACE had two types of undesirable chamber effects:

- o Some modification of the solar radiation environment, and
- o Unnatural wind flow, turbulence, and micrometeorological patterns.

With respect to solar radiation, Allen concluded that both outdoor controlled-environment chambers and open-top chambers gave plants exposure to 80 to 100% of natural full sunlight, although there were some differences in the quality of light in the ultraviolet and near infrared regimes. The natural wind flow and turbulence are quite reduced inside chambers. Kimball (1983) pointed out that this affects water loss. Surano and Shinn (1984) found that the seasonal rate of increase of growing degree days was higher in open-top chambers than for companion plots outside the chambers. The open-top chamber effect on growth is slight, according to research experience on air-pollution effects, but its existence requires that control chambers (without elevated CO_2) be included in the experimental design. Allen (1982) suggests that the micrometeorological differences between chambers and FACE have not been adequately described or evaluated in terms of plant morphogenesis, growth, and development.

The FACE approach has the advantage of least interference with solar radiation and natural wind flow, but creates some effects of its own in terms of spatial and temporal variations in CO_2 concentrations.

SPACE REQUIREMENTS

The FACE technique requires a larger study area relative to the height of the vegetation (H) than do its closest alternatives. Allen (1975, 1979) found that a single line-source FACE release in a maize field required a downstream distance about 7 to 20 times the vegetation height (7 H to 20 H) before horizontal gradients approximately vanish (an equilibrium is reached), when CO_2 release rates were 0.6 to 0.9 kg/m/h and wind speeds at a height of 6 m were as high as 4 m/s.

In computer simulations for a FACE experiment in a tropical forest, Allen, Beladi, and Shinn (1985) found that the plot dimensions approximately scale with H. On the basis of the combined theoretical and experimental experiences above, we would estimate that a plot would need to be 100 H^2 in area (perhaps larger if wind-direction changes are also considered). This means plots of about 100 m^2 for a 1-m-tall wheat field, 484 m^2 for a 2.2-m-tall maize field, and 48400 m^2 (or 4.84 ha), for a 22-m-tall forest.

The air-pollution-exposure systems tend to verify this requirement for a large distance-to-height ratio. The ZAPS system utilized plots with dimensions 73 m x 85 m, or about 100 H on each side for a prairie grassland

(Lee, Preston, and Lewis, 1978). The study at ANL used air-pollution-exposure plots with dimensions 29 m x 27 m, about 50 H on each side, for a soybean crop (Miller et al., 1980). The CERL-designed circular plot array had a diameter of 27 m, or about 30 H for a wheat crop (McLeod, Alexander, and Hatcher, 1983).

A large study area is an advantage when part of the sampling problem is to obtain representative plant material from populations. This is especially a problem in natural ecosystems or forests of uneven age. R.J. Norby (1983) listed carbon-dioxide-cycle flux (litter production, organic matter accumulations, and soil respiration), nutrient cycling, above-ground competition, and phenology as ecological studies requiring a large area of uniform exposure or treatment. On the other hand, as pointed out by E.T. Kanemasu (1983) and by R.L. Desjardins (1983), the requirement for a large area with replication of experiments becomes a logistics problem because processing and analyzing large numbers of samples means higher associated costs, especially in natural ecosystem studies.

The realism of a FACE approach in a large-area natural ecosystem should be considered a "relative" realism. For example, moving materials (air pollution, seed, pollen, and pathogens) and mobile animals (birds, pollinator insects, predators, and herbivores) will cross the experimental boundaries freely, and thus the experiment area will not represent the ecology of an area with naturally elevated CO_2 levels.

METEOROLGICAL REQUIREMENTS

The concentration of carbon dioxide in a large area supplied through a network of pipes will depend inversely on wind speed and directly on the release rate (source) of CO_2 (Allen, 1975; McLeod and Fackrell, 1983). It will also vary inversely with vegetation height when mass consistency is taken into account (Hanna et al., 1982). To hold CO_2 concentration constant on the average, the source must be increased at higher wind speeds. To do this a feedback mechanism must be included in the FACE design, as in the ZAPS and CERL designs.

A difficult problem for perennial experiments, which have never been done before in a FACE study, will be to maintain constant CO_2 under all weather conditions. For example, during calms, the CERL system shuts down to avoid excessive overexposure due to lack of dilution. Since concentration is inversely proportional to wind speed, uncontrollably high CO_2 levels would otherwise result during a calm in a FACE experiment. Changing wind direction is another problem. To avoid directional bias the CERL pipeline network is circular in design and has two height levels of release (McLeod, Alexander, and Hatcher, 1983). Under most conditions only the very center of the circular CERL design will have a uniform horizontal distribution of concentration.

The dilution of gases from the network of pipes has been found to be very drastic close to the release points because the major dilution mechanism is by horizontal advection rather than by turbulent diffusion. That is, the mean horizontal transport of CO_2 is much greater than vertical diffusion by eddy transport. For that reason an approximate "box budget" can be used to make first-order estimates. If we assume that the additional CO_2 (ΔC) vertical distribution is uniform except for a small region close to the release pipeline and that the wind speed (u) in the vegetation canopy is constant, we can derive an equation from the law of continuity. Let an imaginary box be constructed over the release area with height H, width Δy, and length Δx, such that the wind flow is in the x direction. Through the bottom of the box CO_2 flows upward at a (source) release rate Q (mass per unit area per time). In order for mass to be conserved, the outflow through the downwind vertical plane ($uC_{out}\Delta yH$) less the inflow through the upwind vertical plane ($uC_{in}\Delta yH$) must be balanced by the flux through the bottom ($Q\Delta x\Delta y$):

$$Q\Delta x\Delta y = u\Delta yH\ (C_{out} - C_{in}) \quad , \text{ or}$$

$$Q = uH\Delta C/\Delta x \quad . \tag{1}$$

This box budget is a common formula in air pollution meteorology, see, for example, Hanna et al. (1982). From it we can estimate the average increase in CO_2 concentration:

$$\Delta C = Q\Delta x/Hu \quad , \tag{2}$$

and we can define the flushing speed t:

$$t = \Delta x/u \quad . \tag{3}$$

We see that Eq. 2 confirms our former statements of the inverse dependency on wind speed and of maintaining constant elevated CO_2 by increasing Q in high wind speeds. As an example, let us plan to elevate the CO_2 concentration (ΔC) by 100 ppm (183 mg/m^3) for a distance (Δx) of 54 m in a canopy wind speed of 3 m/s and a maize crop 2.2 m tall. We find that the value of the source Q would be 81 $g/m^2/h$, which converts to 810 kg/ha/h.

Allen (1975) computed a value 833 kg/ha/h with a much better model but similar boundary conditions. The flushing rate calculated by use of Eq. 3 for a 54-m plot (Δx) would be 18 seconds.

The Allen (1975) model was two dimensional with a computational grid in a vertical plane parallel to the wind direction. It utilized observed wind-speed and eddy-diffusivity profiles to calculate the CO_2 concentration distribution from a single line source (pipe), or several line sources, perpendicular to the wind direction. The computed isopleths of CO_2 concentration defined a plume of CO_2 that drifted downwind. Some limitations of the model were that it could not include lateral diffusivity (related to turbulence caused by rapid variations in wind direction), and it was a steady-state solution in terms of constant wind direction and wind speed. Nevertheless with some improvements Allen found that the model agreed with observations. Later, Allen, Beladi, and Shinn (1985; attached as Appenxdix) used this model to simulate CO_2 concentrations in a tropical rain forest based on observed wind speed and diffusivity of a Costa Rican forest (Allen and Lemon, 1976).

The model represents a comprehensive FACE evaluation tool and agrees with both the simple box-budget approach, Eq. 2, and with available observations. It provides a means of evaluating alternatives for pipeline-release design, such as heights of release and horizontal variation in rates of release. As stated before, the model determined that a downwind distance of about 10 H is required for uniform horizontal concentrations. Allen, Beladi, and Shinn (1985) concluded that for a tropical rain forest, the CO_2 concentration distribution predicted by the model would be similar (in a relative sense) to that of a maize crop, but that the 40-m-tall forest would require a CO_2 source about 50 to 100 times larger to achieve similar in-canopy CO_2

enrichments. The exact multiplication factor will depend on wind speed and eddy-diffusivity distributions in the two types of vegetation.

Other meteorological requirements should be considered, but are not yet adequately modeled. One is the day-to-day variation in wind direction, which prompted CERL to use a circular grid. Another is the meteorological influence on spatial and temporal variations in CO_2 concentrations in a FACE system.

SPATIAL VARIABILITY

Experience has shown that in all pipeline release systems (FACE, ZAPS, CERL, etc.) there were gradients in the mean concentrations. Harper (1971, 1973a) observed that where the net mean increase (ΔC) of CO_2 was about 100 ppm, the vertical mean gradients near the release pipe (at ground level) were about 200 ppm in 10 cm. Horizontal mean gradients between pipes would also exist, depending on separations between pipes. McLeod, Alexander, and Hatcher (1983) experimented with various CERL configurations of release heights to attain a region of uniform spatial concentration in the center of a circular plot. While the observed spatial variability is a drawback, it seems possible that by clever design of distributed, multi-layer pipeline networks and vertical standpipe releases, such as the CERL approach, coupled with a feedback system of detection and flow controls, some reasonably constant mean CO_2 concentration could be maintained. This puts an added complexity in the design, however, and it may also demand a custom design for each experimental site to allow for local wind conditions and vegetation height and density.

An interplay of spatial and temporal variation in CO_2 concentration also would occur in FACE, because of not only turbulence but also slow fluctuations in the mean wind that change the depth of the CO_2-abundant layer in the plant canopy.

TEMPORAL VARIABILITY

Observations by air-pollution ecologists have shown that air concentrations of an added gas (pollutant or CO_2) in an open system will have a log-normal frequency distribution. McLeod and Fackrell (1983) compared the results of concentration observations by the French Ministry of Agriculture, EPA (ZAPS), University of Nottingham, ANL (ZAPS), CERL, and linear-gradient systems. All had a log-normal frequency distribution of concentration for nearly any time scale, which ranged from a few minutes to a few hours. The geometric standard deviation was such that 10% of the time the observed concentrations exceeded by 3 to 5 times the median concentration for any given location in the grid. This was a useful property for some air-pollution ecologists who were trying to duplicate frequency distributions for air pollution episodes. This kind of fluctuation statistic is not representative, however, of the fluctuation to be expected in globally mixed, elevated carbon dioxide concentrations.

Any released trace gas would undergo rapid entrainment of clean air by a process described by Csanady (1973, p. 225). A cloud of "marked fluid" is apparently subject to dilution by impulses of ambient fluid, but at each successive dilution, the next dilution is likely to be of the same magnitude as the preceding ones; in other words, dilution is geometrically progressive. This type of concentration distribution is commonly observed downwind of a single source. Since the averaging times of a few minutes to a few hours compare with what plants respond to, we can expect wide-ranging variations in

CO_2 concentration about the median concentration at scales that could cause fluctuations in plant response. For example, if the FACE design concentration calls for added CO_2 (ΔC) of 300 ppm then about 10% of the time the concentration would exceed 900 to 1500 ppm. The response time of plants is unknown, but if 6 minutes is a typical stomatal diffusion time, then about once every hour the plant would be subject to this excursion in its internal CO_2 concentration.

Such wide concentration variations may lead to difficulty in interpreting data from experiments where physiological mechanisms are the subject of investigation. Geometric fluctuations would render certain in situ physiological measurements, such as stomatal diffusion resistance, photosynthesis, and water stress, virtually impossible because they depend on quasi-steady-state conditions. Wide fluctuations could cause unnatural response and rate limitations from slower processes in the plant, such as translocation, where the response to highly varying CO_2 concentrations should be quite different from response to steady exposure to elevated CO_2 of the same median value. These difficulties would lead to problems in more elementary research predictions of effects from the experimental result.

The wide concentration variations may be quite acceptable, however, where integration by large numbers of organisms could be readily measured during FACE studies--for example, in biomass determinations. There the cumulative effect is perhaps all that's important. This is an important distinction, because from the agronomic point of view, as in the early days of FACE studies, yield increases were the most significant end product. There may be similar needs in natural ecosystem studies.

SCALE-UP FROM CROPS TO FOREST

As noted previously, the horizontal scale requirement for FACE is a symmetric plot with minimum area of 100 H^2 where H is the height of vegetation. Scaling up from a 2.2-m-tall maize field to a 22-m-tall forest requires about 100 times the plot area (48400 m^2 compared with 484 m^2). Using Eq. (2) to estimate CO_2 requirements, we see that the source Q would not need to be increased to scale up from maize to forest, when Δx scales with H. Using Allen's (1975) estimate for Q of 833 kg/ha/h, to increase CO_2 by 100 ppm the maize plot of 0.0484 ha requires 40 kg/h, but the forest plot of 4.84 ha requires 100 times more, 4000 kg/h. Allen, Beladi, and Shinn (1985) found with their model that 50 to 100 times as much CO_2 would be required for a 40-m forest as for a 2.2-m maize crop.

If the 833 kg/ha/h rate of CO_2 were applied to one 4.8-ha forest plot to attain 100 ppm increase for perennial exposure, the consumption of CO_2 would be about 35,000 metric tons per year (Mg/y). A CO_2 treatment of 300 ppm would require about 105,000 Mg/y. A simple experimental design with one each of the above treatments would require about 140,000 Mg/y. Clearly, scale-up to forests would be very demanding in terms of CO_2 and logistics. The daily consumption of 383 Mg would require a large liquid-CO_2 holding reservoir. About 30 CO_2 receivers, each the size of a tank-truck (13 Mg), would be depleted each day.

Applying FACE to shorter-stature natural ecosystems would be more practical, but here also open-top chambers may work well enough for most purposes. A compromise would be to study forests with a combination of FACE and open-top chamber methods.

COST OF CARBON DIOXIDE

A number of searches have been conducted for naturally occurring CO_2 sources. Zimmerman and Perry (1979) located for the U.S. Department of Energy several naturally occurring subsurface CO_2 gas accumulations in central Mississippi, West Virginia, west Texas, Colorado, Wyoming, New Mexico, and southeast Utah. Some of the gas, such as in Mississippi, contains H_2S and other impurities that render it toxic or expensive to purify. Almost all of the CO_2 gas reserves could be developed to recover oil from residual deposits by miscible-flood, enhanced oil-recovery techniques and may enter that market. The price range used by Zimmerman and Perry (1979) for a profitable CO_2 development was $0.25 to $0.50 per thousand cubic feet (between $5/Mg and $10/Mg at typical temperatures). Enoch et al. (1982) cite wellhead costs estimated at about $20/Mg.

Industrial sources of CO_2 can often be found with comparable prices. Enoch et al. (1982) list coal-gasification plants in North Dakota, New Mexico, and Wyoming that generate CO_2 at about 700 Mg/h with estimated costs of $12/Mg. This production is to be used for enhanced oil recovery. Coyne (1983) found local CO_2 by-product at $30/Mg in Oklahoma.

Retail bulk prices for carbon dioxide depend upon demand. Open-top chamber experiments in North Carolina (Rogers et al., 1983) and in California (Surano and Shinn, 1984) consumed nearly one ton per day at a cost of between $100 to $150/Mg (personal communication) plus rent on a 13-Mg CO_2 receiver of $15 to $20/d.

We can draw a cost comparison as follows. Allen (1975) found that a maize-plot (0.3 ha) FACE required 833 kg/ha/h to enhance CO_2 by 100 ppm. Adding a treatment of 300 ppm would be an additional 2500 kg/ha/h, and the daily consumption of CO_2 for the combined treatments comparable to that of Surano and Shinn (1984) would be 24 Mg/d. For a bulk price from natural or industrial sources between $10 and $30/Mg, sufficient CO_2 would cost $240 to $720/d for FACE. (Recall that a forest study, on the other hand, would cost 50 to 100 times this amount.) The open-top chamber studies of maize by Surano and Shinn (1984) required 1 Mg/d;, at the retail bulk rate of $100 to $150/Mg this would have cost $100 to $150/d. In this case, the ratio of median values is about 4:1 for the cost of FACE relative to the open-top method. For a 120-day maize growing season the cost of CO_2 for FACE would be $28,800 to $86400 and the cost for open-top chambers would be $12,000 to $18,000.

SUMMARY OF FINDINGS

The FACE technique has been tested in the field by agronomists and is similar to a method tried by several air-pollution-ecology studies. It offers less interference with natural wind flow, turbulence, and sunlight when compared with its closest alternatives. Because FACE requires large study plots, on one hand it offers more space for ecological studies, but on the other hand it demands extensive sampling and greater associated costs. The inverse dependence of mean exposure concentration on wind speed requires that a monitoring and feedback control system be included in the FACE design. The distribution of CO_2 within a FACE study plot has been evaluated with the aid of models and experiments and found to require large amounts of CO_2, with the plot size and the source of CO_2 scaling on the square of the vegetation height.

The spatial variability of CO_2 is great near the FACE release pipes, but a clever design using distributed, multi-layer pipeline and standpipe releases coupled with the monitoring and feedback system would improve uniformity. The temporal variability of a FACE system, however, is much greater than its closest alternatives. That is, the log-normal frequency distribution of concentrations, which is inherent in the mode of dilution, produces excursions in high concentrations far too frequently. This property of wide concentration fluctuations in FACE renders it unlikely to be used for mechanistic studies, such as of photosynthesis, but it may be satisfactory to study biomass accumulation and other ecosystem processes that are integrating in nature.

Scale-up from crops (where FACE has been demonstrated) to forests will require 50 to 100 times as much CO_2 per plot as for crops because of the dependence of plot size on the square of the vegetation height. The volume rate of CO_2 required in a perennial FACE forest study would exceed 100,000 tons (metric) per year, which is logistically very difficult or impossible.

RECOMMENDATIONS

It appears that the FACE method is well understood with a substantial base of theoretical and experimental experience. The chief advantage of the FACE approach is that it interferes less with natural wind flow and turbulence than do alternatives such as open-top chambers. But the FACE approach has difficulties, too, chief among them the wide variations in CO_2 concentration that render mechanistic studies of photosynthesis, etc., virtually impossible.

FACE does not seem to be a viable alternative for perennial studies in forests, because the volume flux of CO_2 required would be enormous. The discharge of CO_2 would be a couple of hundred metric tons per day at a cost of several thousand dollars per day (even at the wellhead CO_2 prices) with annual expenditures in millions of dollars (even for a simple experimental design). Because the other alternative semi-enclosed methods such as open-top chambers have rarely been used in forests, there is clearly a need for methods development here. The scale-up costs for open-top or alternative semi-enclosed designs should be investigated before taking on a FACE experiment in a forest.

For vegetation of shorter stature, the FACE requirements for plot area and CO_2 source are within reason. At this end of the spectrum are grassland and crop studies, where one has to choose between FACE and its variable CO_2 problem or alternative methods with chamber effects. The logistics of FACE in this case is not much of an issue. If selected, the FACE design should be based on the CERL circular array for best effect.

In the middle ground are natural ecosystems of intermediate stature: immature forests, shrubland, etc., where the ecological questions may be important enough to apply a FACE technique for questions on litterfall, nutrient cycling, and competition, for example. Here the investigator should choose FACE, again in the CERL configuration, when he can accept the concentration fluctuations and look for integrated effects. In practice, a combination of enclosed, semi-enclosed, and FACE should be the solution.

Our recommendations are therefore to limit the application of FACE to studies of natural ecosystems that are between 1 and 3 meters tall and where the large plot size is an advantage in terms of examining higher-order ecological questions. In this case the use of other methods such as open-top chambers would permit mechanistic studies of individual plants, while FACE would be appropriate for aggregates of plants representative of a larger population. It seems logical that this should be a combination approach.

The question of how to study tall forests remains unanswered unless the study is confined to immature individuals within the size range above. Additional developments and feasibility studies are needed.

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Appendix

Modeling the Feasibility of Free-Air Carbon Dioxide Releases for Vegetation Response Research

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MODELING THE FEASIBILITY OF FREE-AIR CARBON DIOXIDE RELEASES FOR VEGETATION RESPONSE RESEARCH

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1. INTRODUCTION

Carbon dioxide concentration of the atmosphere has been increasing steadily from 315 parts per million, mole fraction basis (ppm) in 1958 to about 345 ppm currently (Keeling et al., 1982). Most of this recent rapid rise in CO_2 has been attributed to burning of fossil fuels. One of the early concerns was that CO_2, an atmospheric "greenhouse-effect gas", could cause global surface temperatures to rise if the atmospheric concentrations increased. Recent General Circulation Models (GCM) of climate supported this concept (e.g., Manabe and Wetherald, 1980). A panel of scientists concurred with these evaluations, and concluded that global surface temperatures could rise from 1.5 to 4.5°C with a doubling of atmospheric CO_2 (National Academy of Science, 1983).

Another factor that has received increasing attention is the role of CO_2 in photosynthesis and growth of agricultural crops and ecological systems (Kimball, 1983; Lemon, 1983; Wittwer, 1983). Most of the carbon of higher terrestrial green plants is taken up from the atmosphere. Voluminous literature shows that leaf and whole-plant net photosynthetic rates increase as CO_2 concentration is increased. Kimball (1983) summarized much of the available literature and found that plant yields would increase about 33% for a doubling of CO_2. Since some scenarios predict a doubling of atmospheric CO_2 in less than 100 years, the importance of changing CO_2 on green plants was recognized. Information has been summarized and recommendations for research developed at an International Symposium on CO_2 and Plants (Lemon, 1983).

2. RATIONALE FOR FREE-AIR CO_2 ENRICHMENT

Allen (1979) and Baker et al. (1982) reviewed several experimental approaches for studying effects of increased CO_2 on plants, which included field releases of CO_2, open-top field chambers, sunlit controlled-environment chambers, greenhouses, artificially-lit controlled environment chambers, leaf chambers, and simulation models. Baker et al. (1982) recommended sunlit controlled-environment chambers and open-top field chambers for long-term CO_2 enrichment studies, with leaf chambers included to provide detailed responses at the individual leaf level. They did not recommend free-air CO_2 releases at that time, partly because of the reports by Allen (1975; 1979) of low efficiency of capture of CO_2 which would require massive quantities of the gas to be released to maintain high CO_2 concentrations.

Recent studies of plant responses to CO_2 in open-top chambers have shown that plants grown in nonenriched control chambers responded differently compared to outside plants nearby (Rogers et al., 1983; 1984). These chamber influences and the need to measure responses in undisturbed ecosystems led to reconsidering the feasibility of free-air CO_2 enrichment (FACE) as a research technique for measuring the response of vegetation to CO_2. Furthermore, large geologic CO_2 sources are available (Enoch, 1984).

2.1 Disadvantages of free-air CO_2 enrichment

The first disadvantage is the high cost of the large volumes of CO_2 required for field scale CO_2 enrichment. Other problems are the variable spatial and temporal distributions of CO_2 concentration induced by variable wind (speed and direction) and turbulent diffusion. Even under steady-state conditions, CO_2 concentration would vary drastically with height above ground, if the CO_2 source were at ground level. Temporal distributions could range from those associated with long-term windspeed changes to those associated with short-term turbulence. Very large "instantaneous" fluctuations in CO_2 concentration could occur with CO_2 releases in the open field, and we do not know what the photosynthetic and growth effects may be. These problems have been reviewed by Allen (1979) and Baker et al. (1982).

2.2 Advantages of free-air CO_2 enrichment

The advantages are somewhat obvious; no modification of the crop or ecosystem microclimate by the experimental apparatus. Natural sunlight and natural, outdoor wind movement and energy exchange processes could be maintained during a FACE study. This should eliminate some of the types of plant morphological modifications that have been observed in chamber studies (e.g., longer internodes and weaker stems of soybeans). This would give more confidence in assessing real-world response of vegetation to CO_2 if the major disadvantages of section 2.1 can be overcome and if the other disadvantages can be shown to be unimportant.

3. SIMULATION OF FREE-AIR CO_2 ENRICHMENT

3.1 Simulation Methods

A two-dimensional numerical model was used to account for horizontal mass transport and vertical eddy diffusivity of CO_2 (Allen, 1975). The model had eleven cells in the vertical dimension and 60 cells in the downwind horizontal direction. Twenty-seven of these cells contained adjacent release lines to simulate area source releases. The model was dynamic; CO_2 transport was tracked at small enough time steps to preperve numerical stability until steady-state CO_2 distributions were achieved. Data were displayed by CO_2 concentration isopleths.

3.2 Simulation Factors

The effects of the following factors on steady-state distribution of CO_2 concentrations were investigated. They included height of vegetation, windspeed and eddy diffusivity, CO_2 release rates, CO_2 release heights, and several arrangements of release points of the CO_2 release system.

Vegetation heights in the FACE simulations included 40 m (tropical rainforest), 25 m (temperate forest), 2.2 m (agricultural crop), and 0.3 m (grassland). The results presented later will focus on contrasts between the tallest and shortest vegetation. Results of simulations for a 2.2-m agricultural crop were reported earlier by Allen (1975).

Windspeeds (U) and eddy diffusivities (K) were varied concomitantly by approximating K_z to be linearly related to U_z as U was either increased or decreased. Three cases were simulated: reference windspeed, low windspeed = 0.5 x reference, and high windspeed = 3 x reference. Reference windspeed was 4.4 m/s and K was 26.2 m^2/s at the top gridpoint (100 m) of the tropical rainforest simulations, and 3.1 m/s and 1.15 m^2/s, respectively, at the top gridpoint (6 m) of the grassland simulations. These values were derived from data of Lemon et al. (1970) and Ripley and Redmann (1976).

Carbon dioxide release heights at ground level and at about 3/4 vegetation height were used in the FACE simulations for the tall tropical rain forest, and at about twice vegetation height for the short grassland. The areal release rate was 4500 kg/h for the tall forest (270 m x 270 m) or 1667 kg/(ha-h), and 250 kg/h for the grassland (13.5 m x 13.5 m) or 1852 kg/(ha-h). Since little of the total amount of CO_2 was taken up by the vegetation, rates of release and relative CO_2 enrichment above a packground of 340 ppm could be made proportional so that only one release rate was required to illustrate CO_2 concentration distribution in and above a canopy. The methods of CO_2 release that were used in simulation were constant rate area-source releases, variable rate releases along the windpath, and an upwind border vertical line source release (backup release) to adjust the CO_2 concentration of the air flowing into the bottom six cells of the test area. The variable rate release along the windpath was an exponentially decreasing function, weighted so that the total release was the same as the constant rate area-source. The upwind vertical line source was used in conjunction with one of the two area sources (at ground level or at elevated height). The rates of release at the lowest six gridpoints of the vertical line source were made proportional to the windspeed, eddy diffusivity, and height increment of each cell. The amount of CO_2 released per hour was the same as the area source (e.g., either 4500 kg/h for the 40-m vegetation or 250 kg/h for the 0.3-m vegetation).

4. FACE SIMULATIONS: RESULTS AND FINDINGS

4.1 40-m vegetation

The constant area-source release at ground level gave CO_2 concentration isopleths that increased with height as downwind distance increased (Fig. 1). The exponentially decreasing area-source release gave some improvement, but still did not give reasonably uniform CO_2 concentrations at the top of the canopy. The combination of exponential release (4500 kg/h) plus vertical line backup release (4500 kg/h) gave a reasonably uniform enrichment of about 100 ppm CO_2 at the top of the canopy (Fig. 2). As expected, raising the windspeed and eddy diffusivity by a factor of three reduced the enrichment to about 30 ppm CO_2, and reducing the windspeed and eddy diffusivity by a factor of 2 increased the enrichment to about 200 ppm (not illustrated).

Regardless of the method of enrichment with ground level releases, the CO_2 concentrations increased with depth in the canopy. This problem is unavoidable with any ground-level release (Figs. 1 and 2).

Raised area source releases tended to produce high concentrations in the plane of release, but they were not as uniform with downwind distance in the top canopy layers (not illustrated) as the ground level area source releases.

4.2 0.3-m vegetation

Ground-level releases appeared to give CO_2 concentrations that varied downwind in the top of the plant canopy (not illustrated). The horizontally uniform area source release at a height of 0.65 m with vertical backup appeared to give the most uniform concentrations near the top of the canopy (Fig. 3). As in the case of the tall vegetation, changing windspeed and eddy diffusivity affected the level of CO_2 enrichment inversely (not illustrated).

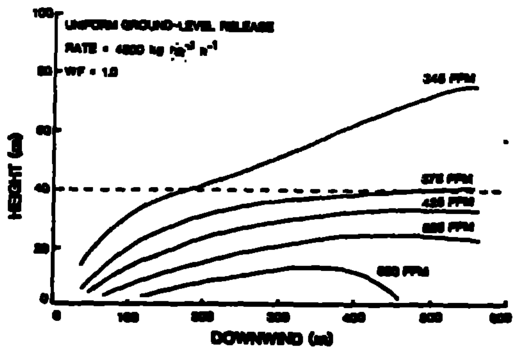

Fig. 1. CO_2 concentration isopleths that show nonuniform distribution of CO_2 both vertically and along the windpath for a ground-level CO_2 release simulation in a 40-m tropical rainforest.

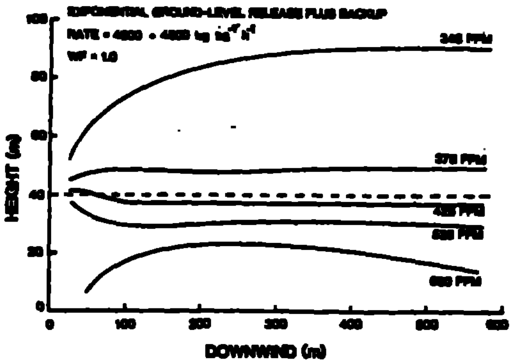

Fig. 2. CO_2 concentration isopleths that show a relatively uniform CO_2 concentration in the top canopy levels of a 40-m tropical rainforest for a simulated ground level plus backup vertical line source CO_2 release.

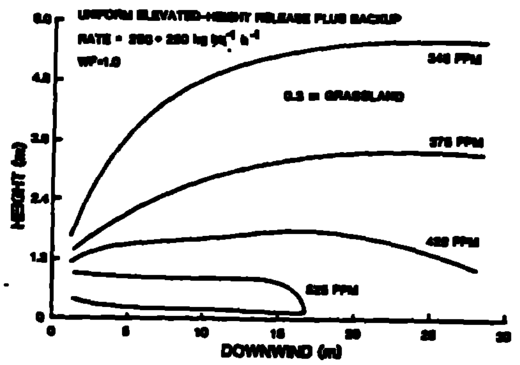

Fig. 3. CO_2 concentration isopleths that show relatively uniform CO_2 concentrations near the top of a 0.3-m grassland for a simulated elevated height plus backup vertical line source CO_2 release.

4.3 Summary and conclusions

A vertical line-source backup appears to be required in every case to establish quickly a uniform CO_2 concentration near the top of the canopy. For ground level releases, an exponentially-decreasing area-source with vertical backup appears to give a more uniform CO_2 distribution near the top of the canopies. For elevated-height releases, a uniform area-source with vertical backup appears to give a better CO_2 distribution.

We expect that reversing the modeling process could give a better description of the ideal release system. For example, if the desired CO_2 concentrations were specified in each cell, then the CO_2 input rates to each cell required to equilibrate the 2-dimensional system could be computed. From a detailed simulated FACE injection system, a practical release system could be designed with a limited number of injection points or lines which would give a reasonably uniform concentration of CO_2 throughout a test area.

The FACE simulations showed that reasonably uniform elevated CO_2 concentrations can be produced in vegetation under steady-state conditions. However, to maintain these average elevated CO_2 concentrations under variable mean windspeed and direction conditions is an engineering and sampling feedback control problem which should be addressed. Much of the needed technology for a FACE delivery and feedback control system has already been developed in air pollution studies (e.g., McLeod et al., 1983; McLeod and Fackrell, 1983; Miller et al., 1980) as reviewed by Shinn and Allen (1985).

Since in most locations wind may be from any direction, these simulations assumed that a large circular area or square would have to be designed to elevate CO_2 concentrations somewhat uniformly regardless of wind direction. If a location for FACE could be found with one predominant wind direction, then it would be possible to simplify the problem and develop a CO_2 concentration gradient FACE experiment rather than a uniform CO_2 concentration system.

5. COST ESTIMATES

Costs of CO_2 for these simulated releases were computed from the release rates for a 365 day period, assuming releases for 12 hours per day, a CO_2 cost of $39 per Mg, and a square block to be uniformly enriched with an area-source plus vertical line source backup system.

5.1 40-m forest

For the simulated 270 m downwind distance, assuming a 270 m crosswind distance the release rates used were 4500 kg/h from the area source plus 4500 kg/h from the backup vertical line source. The cost of the CO_2 would be $948 per hour, or $4.15 million per year. On a per hectare basis, this would be $130 per hour or $570,000 per year.

5.2 0.3-m grassland

The downwind release distance was 13.5 m.

On a square block basis the CO_2 release rates simulated were 250 kg/h for the area source plus 250 kg/h for the backup vertical line source. The costs of CO_2 would be \$2.62 per hour, or \$11,500 per year.[2] For comparison, on a per hectare basis, the cost for CO_2 would be \$144 per hour or \$630,000 per year.

5.3 Cost limits

These estimates suggest that the CO_2 required to enrich the tall forest could be up to 1000 times greater than that needed to enrich a suitable area of a short grassland. The practical limit for size of vegetation for use of free-air CO_2 enrichment is obviously much smaller than a 40-m^2 tropical forest. Although cost estimates have not been made, this technique may be economically feasible for research purposes for vegetation as tall as most agricultural crops or seedling trees. Beyond those heights, CO_2 costs become prohibitive, not to mention the problems of installation and servicing of a CO_2 field release system, a spatial sampling network, and a feedback control system for maintaining CO_2 concentrations. Shinn and Allen (1985) have provided a more complete analysis of the effect of vegetation size scale on the amount of CO_2 required for a FACE study, and a more complete discussion of the range of probable costs of CO_2.

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